SOME OBSERVATIONS ON THE MOVEMENTS OF UNDERGROUND WATER IN CONFINED BASINS

A. R. SCHULTZ
U. S. Geological Survey, Washington, D. C

In 1905, while pursuing my geologic studies at the University of Chicago, I had an opportunity of doing some experimental work on the motion of underground waters in confined basins. Although the time and equipment for experimentation were limited, an attempt was made to ascertain as nearly as possible from a given set of conditions what effect distance from the outcrop area has upon the flow or yield of a well; how an increase in head modifies the flow or yield of a well; with what regularity friction increases as the distance from the outcrop area is increased; and what effect confined air between the water table and a surface layer of water has upon the water level in a well. It is not supposed that any rigid deductions can be made from a set of single experiments. It is necessary, before making such deductions, that several kinds of material be tested under somewhat different conditions to see whether or not they agree in the essential points. For this reason no deductions will be made, but the facts observed in the experiment are recorded and may be compared with known conditions in other artesian basins.

To determine the above factors a miniature artesian basin was arranged in the basement of Walker Museum and the experiment begun. The basin consisted of an eight-inch steam pipe 40 feet long, and closed at one end. The pipe was placed in position as shown in Fig. 1, and then filled with clean, dry sand, packed as firmly as possible by tamping the sand with a rod as the pipe was being filled. Five $\frac{3}{8}$-inch wells were drilled at points *A*, *B*, *C*, *D*, and *E*. In each of these wells was inserted a casing $\frac{1}{4}$-inch in diameter and 9 inches long. The lower 8 inches, which extended down into the sand consisted of a cylindrical wire screen, surrounded on the outside by one thickness of cheese-cloth to prevent the finer sand grains from being washed into the well and filling it. The upper portion of the casing, which projected through the steam pipe and furnished the ground connection of the well, was a cylindrical brass tube $\frac{1}{4}$-inch in diam-

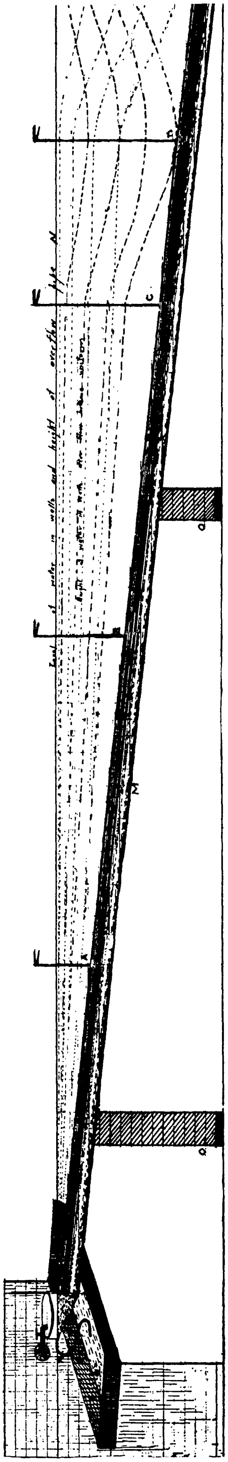

FIG. 1.—Diagram showing the arrangement of a miniature artesian basin.

eter and one inch in length, to which the lower 8 inches were soldered. When the casing was in place the remaining space in the well outside the casing was filled with sand and the space between the brass well casing and the iron pipe sealed, making a water-tight contact and leaving no passage for the water within the iron pipe except through one of the five wells. Above ground or outside the iron pipe each well casing was connected with $\frac{1}{4}$-inch rubber tubing, long enough to extend higher than the intake of the iron pipe. To facilitate reading the height to which the water in the well rose and to make it easier to collect the water flowing from the wells, the end of each tubing was provided with a foot of $\frac{1}{4}$-inch glass tubing bent at right angles as shown in diagram.

With the apparatus in position as above shown, the water was turned on and the sand within the pipe allowed to absorb as much water as possible—the surplus escaping through the overflow pipe *N*. In order to ascertain with what velocity the water flowed through the pipe the tubing at well *E* was disconnected at the brass casing and an indicator to report the final arrival of water inserted into well *E*. The time from the turning on of the water until it arrived at *E* was found to be 25 hours and 40 minutes. The velocity was therefore 1.56 feet per hour or .31 inches per minute. The average diameter of the sand grains as determined by measurement of 1,000 grains was .43$^{\mathrm{mm}}$ and the porosity of the sand 39.2 per cent.

The tubing at well *E* was replaced and in a short time the water in each well stood

at the same level as the overflow pipe. The basin was saturated, the water ponded, and no more water entered the sand, but all escaped through the overflow pipe.

It was believed that the water flowing through the pipe would readjust the sand particles and succeed in packing them into smaller space than was done on filling the pipe with sand. To accomplish this the well tubing at each well was placed in a receptacle on the floor of the basement, and the water allowed to flow freely from the wells. At short intervals the pipe was revolved in order to assist in packing the sand. This process was continued for two days, and as the sand settled in the pipe a new supply was added at the intake. When the pipe was entirely filled and no further settling took place the wells were put back in position shown in Fig. 1, and the water in the wells soon stood at the level of the overflow pipe. A constant head was maintained at the intake by allowing enough water to flow so that a small stream or the surplus water escaped through the overflow pipe.

Tests were now made to ascertain the yield per well at different heads. The water at one of the wells was allowed to flow at a given head until the flow became constant. The head was then increased and maintained until the flow again became constant, and so on until each well in turn was tested.

The test at each well was begun only after the water in all the wells stood on a level with the overflow pipe and they were, therefore, independent of each other. The flow or yield per well at a given head was determined by collecting the discharge per minute, as timed by a stop watch, and weighing the water thus collected. The results obtained in this test are set forth in the tables appearing on the following pages.

Another series of tests were made similar to those in Table I. This time, however, the flows at the various wells were not given time to become constant. Each measurement at the five wells was taken only after the water in all the wells stood on a level with the overflow pipe. After each measurement time was allowed for the water to regain its normal condition. The figures therefore in this table indicate the flow during the first minute after the well is allowed to flow at a certain head.

TABLE I

SHOWING DECREASE IN FLOW DURING THE FIRST STAGES OF PRODUCTIVE WELL AND THE INCREASED YIELD DUE TO INCREASED PRESSURE

WELL	TIME INTERVAL AT WHICH FLOW WAS TESTED	FLOW IN GRAMS PER MINUTE			
		1 Ft. Head	2 Ft. Head	3 Ft. Head	4 Ft. Head
	Minutes				
	0	245			
	10	220			
	20	195			
	30	165			
	40	142			
	50	120			
A	60	110			
	70	100			
	80	91			
	90	82			
	100	84			
	110	82			
	120	82			
	0	216	365		
	10		330		
	20	198	305		
	30	180	285		
	40	166	256		
	50	150	225		
	60	135	205		
B......	70	115	182		
	80	99	166		
	90	89	161		
	100	88	159		
	110	89	159		
	120	89	159		
	130	89	159		
	Increase in flow		70 g or 79%		
	0	215	325	370	
	10	199	308	346	
	20	190	291	324	
	30	172	271	310	
	40	160	252	289	
	50	151	230	278	
	60	145	215	265	
C......	70	136	198	252	
	80	116	184	245	
	90	106	170	237	
	100	99	164	236	
	110	91	162	237	
	120	91	162	235	
	130	91	165	236	
	Increase in flow		74 g or 81%	71 g or 78%	

TABLE I—*Continued*

Wells	Time Interval at Which Flow Was Tested	Flow in Grams per Minute			
		1 Ft. Head	2 Ft. Head	3 Ft. Head	4 Ft. Head
D.....	0	225	351	390	420
	10	195	332		
	20	180	310	345	
	30	160	290	330	370
	40	150	270	315	356
	50	138	240	289	340
	60	123	220	268	328
	70	110	205	252	310
	80	100	190	228	208
	90	92	172	222	290
	100	91	129	219	286
	110	90	154	220	284
	120	89	154	220	284
	130	90	154	220	284
	Increase in flow		64 g or 71%	66 g or 73%	64 g or 71%
E......	0	166	179	198	215
	10	140	155	172	203
	20		122	160	192
	30		105	151	180
	40	64	96	140	171
	50	56	95	128	160
	60	50	83	120	156
	70	48	83	115	152
	80	48.2	83	115	150
	90	48.3	83		150.2
	100	48.2		115	150.4
	110	48.2			
	120		83	115	150
	130	48	83	115	150
	Increase in flow		35 g or 73%	32 g or 67%	35 g or 73%

On examining the above two tables it is evident that the flow at each of the wells for a given head is about the same. Well *D* at a given head furnished as much water as well *A*, *B*, or *C*, although its distance from the outcrop is much greater. Well *E* is the only exception. The decrease in yield here is due, no doubt, to the nearness of the well to the end of the pipe which greatly reduces the area supplying the well.

The flow or yield per well does not increase at the same rate as the pressure but lags somewhat behind. As determined from the various measurements recorded in Tables I and II, the flow or yield per well approximates 73 per cent. of the increase in pressure or head. In other words, doubling the head increases the flow by about 73 per cent. In a test made by Professor Turneaure for the Madison waterworks

TABLE II

SHOWING THE INCREASE IN FLOW DUE TO INCREASE IN HEAD

Wells	Flow in Grams per Minute			
	1 Ft. Head	2 Ft. Head	3 Ft. Head	4 Ft. Head
A.....	245 Increase in flow			
B.....	216 Increase in flow	388 172 or 71 %		
C.....	215 Increase in flow	383 168 or 78%	540 157 or 73%	
D.....	225 Increase in flow	390 165 or 73%	555 165 or 73%	710 155 or 72%
E.....	166 Increase in flow	279 113 or 68%	397 118 or 71%	516 119 or 71%

Commissioners in 1903 the capacity of the Main Street well (No. 10) at Madison, Wis. (see Fig. 2), was found to be 599,000 gallons per day when the water stood 18 feet below the surface. On lowering the water to a depth of 72 feet below the surface the yield was increased to 1,500,000 gallons per day, the increase in flow being only 63 per cent. of the increase in head.

Table I shows that the flow at any well was at a maximum when the well was first tapped or allowed to flow. The flow then gradually decreased and finally became constant. During this decrease in flow the water in the remaining wells gradually lowered and readjusted itself. The final position of the water in the wells after the flow became uniform in wells *D* and *E* is shown by the dotted lines in Fig. 1. The greater flow during the first stages is probably due to the fact that the water immediately adjacent to the well finds ready entrance into the well with comparatively little friction. As the water farther from the well is drawn upon, the friction becomes greater and greater as the distance the water moves through the sand particles increases, and the yield consequently less and less. Finally the well adjusts itself to its new conditions of head and friction, and the yield becomes fairly uniform.

The point of interest here is that the wells farthest from the intake yield as strong a flow as those one-third or one-fourth the distance

from the intake. This suggests that the friction which is the cause of cutting down the flow is restricted largely to the vicinity of the well where the water is moving with the greatest velocity. Much the same conditions probably exist in the Wisconsin artesian basin, where in the vicinity of Green Bay, Milwaukee, Wis., and Chicago, Ill., the head has been reduced approximately 100 feet since the first flowing wells were put down, while many of the wells between these locations and the intake area have practically the same head as when first drilled. Recent wells drilled between the above-named localities and the outcrop region show that there is no corresponding decrease in head to that noted in the vicinity of Green Bay, Milwaukee, and Chicago. It follows, therefore, that through the major distance of the sandstone the friction of the water is almost zero, or the pressure at the wells would not so nearly equal the pressure due to head.

When wells are allowed to flow or are heavily pumped, the pressure in the vicinity of the well rapidly drops, while at a distance of several thousand feet the pressure is often as great while the well is flowing or heavily pumped as it was before the flow or pumping began.

That the influence of a well extends to a very considerable distance is shown in a general way by the following tests made in Madison, Wis., by the Waterworks Department in 1903 (for location of wells see Fig. 2):

	No. Gallons per Day
1. One well at the pumping station yields	500,000
2. Four wells at the pumping station yield	1,000,000
3. Four wells at the pumping station, and four wells scattered along a line 3,000 feet long yield	1,750,000
4. Four wells at pumping station and one remote well yield	1,300,000
5. Main Street pump (Well No. 10), not running the Blount Street well (No. 8), yields	984,000
While the remainder of the wells yield	2,240,000
6. Main Street and Blount Street pumps both running, the two wells yield	1,944,000
(or nearly twice the yield of the Blount Street well in Par. 5) while the remainder of the wells yield	1,300,000

When the Madison wells were first drilled the water overflowed 4.5 feet above Lake Mendota, or 854.5 feet above tide. At present propeller pumps are installed at the Main Street well (No. 10) and

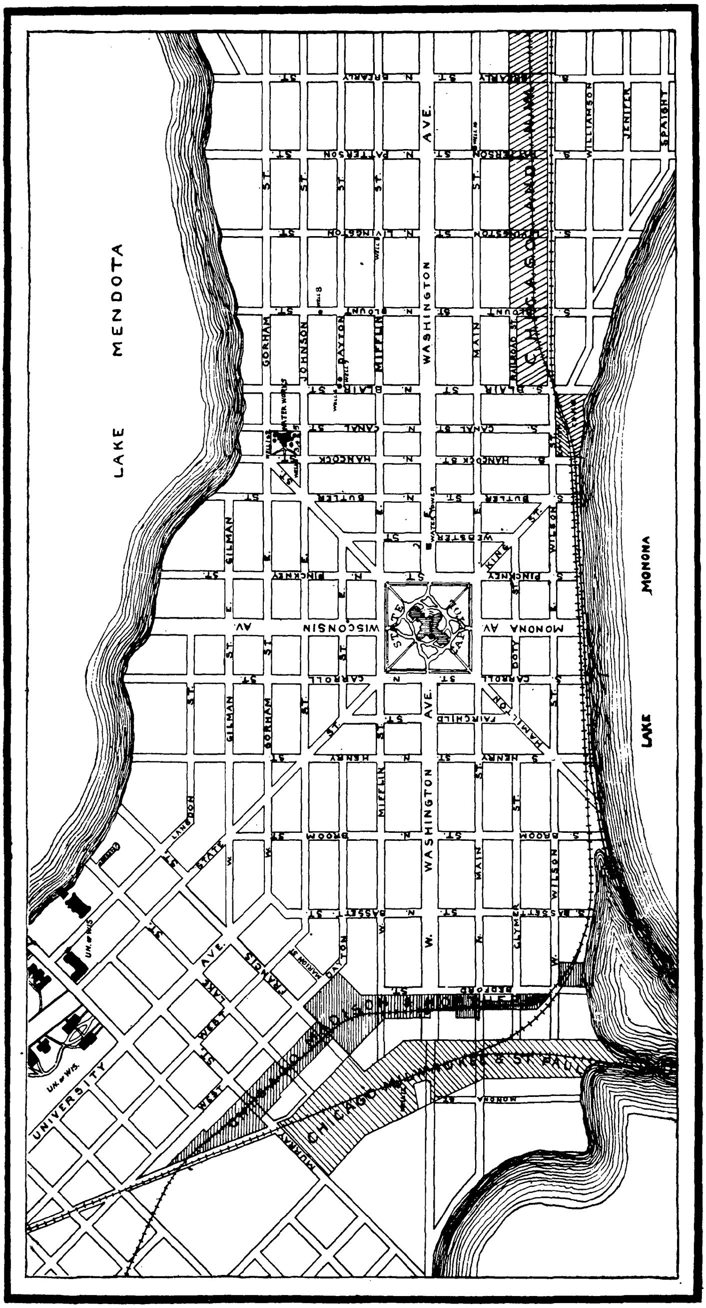

FIG. 2.—Map showing the location of artesian wells in Madison, Wis.

DESCRIPTION OF FIG. 2

		Diameter	Depth	Owner
Well	1	8 inches	751 feet	City of Madison (Waterworks)
"	2	8 "	226 "	City of Madison (Waterworks)
"	3	6 "	751 "	City of Madison (Waterworks)
"	4	6 "	751 "	City of Madison (Waterworks)
"	5	8 "	751 "	City of Madison (Waterworks)
"	6	8 "	751 "	City of Madison (Waterworks)
"	7	8 "	226 "	City of Madison (Waterworks)
"	8	8 "	751 "	City of Madison (Waterworks)
"	9	10 "	821 "	City of Madison (Waterworks)
"	10	10 "	736 "	City of Madison (Waterworks)
"	11		1015 "	State of Wisconsin
"	12		795 "	Chicago, Milwaukee & St. Paul Ry. Co.

Blount Street well (No. 8). All other wells (see Fig. 2) are connected with the suction of the pumps at the pumping station. The Main Street well is scarcely affected, while the pumps at the pumping station, with a vacuum of about 18 inches, are drawing water. The nearest well of the group, the Livingston Street well or No. 9, is only 1,000 feet from the Main Street well No. 10. When the Blount Street propeller pump is working and the water in the well lowered 72 feet, the water in the Main Street well, 2,000 feet from the Blount Street well, recedes about 14 feet, and then remains stationary. Tests of well No. 12 at the C. M. & St. Paul roundhouse, a mile distant, fail to show any effect of the pumping at the city well, even while the water in the wells No. 10 and No. 8 was 72 jeet below the surface and the total capacity of all the wells was 3,200,000 gallons per day.

As clearly indicated by the experiment and by the above tests the drop in the water level in the vicinity of a well is not due so much to the friction through the major course of the water where the movement is slow, but is chiefly due to the friction in the vicinity of the well, where the water is moving on its way to the well and on through the casing itself until it reaches the surface. Back a short distance from the well the water oozes slowly from the small openings and maintains the same head as before the well was pumped or allowed to flow.

Several tests were made to see what effect confined air between the water table and the gathering ground would have upon the water level in the wells. During this experiment well *A* was sealed so that no air could escape through it. The water in the pipe stood 1 foot 2 inches below the escape pipe, when water was turned on and the

sand at the outcrop allowed to absorb as much of the water as possible. Ten minutes after the water was turned on the water in the wells stood 1 foot below the escape pipe, indicating a rise of the water in the wells of two inches. Occasionally air bubbles would escape at the intake, causing a slight fluctuation of the water in the wells. On opening well *A* and allowing the air to escape, the pressure of which was strong enough to force paper away from the mouth of the well, the water in the wells *B*, *C*, *D*, and *E* dropped back to its original level, 1 foot 2 inches below the escape pipe, thereby showing that none of the water recently added to confine the air had reached the water table.

The water in the pipe was now lowered to 2 feet 11 inches below the overflow pipe, the other conditions being the same as in the first test. Ten minutes after water was turned on, the head at wells *B*, *C*, *D*, and *E* was 2 feet 9 inches below the overflow pipe. The pressure on the confined air increases as the sand absorbs more water, and when the pressure becomes great enough some of the air rises through the sand and water and escapes at the outcrop. The instant a large bubble of air escapes there is a very slight drop in the water level in the wells.

Thirty minutes after the water was turned on the water in the wells *B*, *C*, *D*, and *E*, stood 2 feet 8.5 inches below the escape pipe, indicating a rise of 2.5 inches. On opening well *A* and allowing the confined air to escape the water in wells *B*, *C*, *D*, and *E* dropped back to 2 feet 11 inches, thereby indicating that none of the recently added water had been added to the water table. The rise of the water in the wells in both of these cases was therefore due to the confined air between the water table and the newly added water layer near the intake; a condition which to a greater or less degree prevails during every rain storm, when the water absorbed by the surface shuts in more or less air between the surface layer of water and the water table. The effect of this additional pressure upon the yield at springs or wells is evident.

In a region of flowing wells like that of southern Wisconsin and northern Illinois where the porous beds are saturated with water and the water more or less ponded, the yield at any given well depends largely upon the conditions of the beds in the immediate vicinity of

the well, and not so much upon the transmitting power of the porous beds between the well and the outcrop area. As indicated by the tests in this experiment, as well as in the Madison test above cited, the disturbance caused by the water, escaping at a well, soon dies out as the distance from the well becomes greater and greater. Seldom in the Wisconsin district does the disturbance extend more than a mile back from the well.

The movement of the water in these ponded basins is very slow. In the Wisconsin area where the annual precipitation approximates 30 inches, probably not more than one fifth or 20 per cent. of this amount is added to the ponded sea. On the other hand it may be considerably less than 20 per cent., for no accurate determinations are at hand which give the exact amount of run-off in the Wisconsin region. To the amount of immediate run-off must also be added the amount that returns to the surface by evaporation, by vegetation, springs, and shallow wells.

Assuming, however, that 20 per cent. is a fair estimate of the amount of precipitation that is added to the ponded sea and that $16\frac{2}{3}$[1] is the average pore space of the Potsdam sandstone, we can compute the rate of flow.

In order that 20 per cent. of the precipitation may be added to the ponded sea without raising the water level, the increment of the previous year must have moved vertically downward 3.6 feet.

The dip of the Potsdam sandstone as indicated by wells between Madison, Wis., and Chicago, Ill., is about 12 feet per mile. It follows, therefore, that the lateral movement of the water amounts to 1760 feet per year or one-third of a mile. As much of the Potsdam sandstone gathering ground lies 200 miles northwest of Chicago, it is evident that the water collected by the catchment area will require in the neighborhood of 600 years before it reaches Chicago. If the average pore space of the sandstone is larger than $16\frac{2}{3}$, the downward movement of the water as above computed would be less, and if the pore space was smaller, the downward movement would have to be greater, in order to hold the 20 per cent. of the precipitation. It also follows

[1] C. R. Van Hise, "A Treatise on Metamorphism." Monograph 47. *U. S. Geological Survey*, pp. 585–89.

that the coarser the sandstone and the more porous, the greater will be the amount of water available at any given well.

That the pore space in many cases is larger is evident. For example in the Prairie du Chien well, drilled in 1903, for the Sanitarium, a coarse bed of sandstone was entered at 720 feet below the surface and continued down to 805 feet, passing through 85 feet of coarse porous sandstone. The pore space of this sand as determined by the writer from several samples taken from the well was found to be 30. The size of the sand grains were very large, making this 85 feet horizon by far the strongest flow of water struck in the well. The average size of grain as determined by measuring 1,000 representative grains was $.92^{mm}$.

The maximum and minimum dimensions of eleven of the larger grains are tabulated below and give a fair idea of the coarseness of the sand grains.

TABLE III

DIMENSIONS OF SAND GRAINS IN POTSDAM SANDSTONE, PRAIRIE DU CHIEN, WISCONSIN

	Minimum Dimension	Maximum Dimension	Average
1......	2.43^{mm}	5.35^{mm}	3.98^{mm}
2......	3.32	3.47	2.39
3......	2.30	3.26	2.78
4......	2.00	3.30	2.60
5......	1.29	3.38	2.34
6......	1.80	2.93	2.36
7......	1.70	3.08	2.39
8......	1.51	3.22	2.37
9......	1.50	2.84	2.17
10......	1.55	2.70	2.12
11......	1.60	2.56	2.08
			2.50